Advanced MR Coronary Imaging at 3.0T: Promises and Problems

Debiao Li, Ph.D., Xiaoming Bi, M.S.
Departments of Radiology and Biomedical Engineering
Northwestern University, Chicago, IL

Background

Conventional x-ray angiography has been the gold standard for the diagnosis of coronary artery disease for decades. Such procedure requires catheterization of the patients and is invasive and expensive. MRI provides a noninvasive way of visualizing coronary arteries without exposing patients and medical personnel to excessive radiation.

MRI has been quite successful in many areas such as brain imaging and evaluation of cardiac function. Since the first reports of visualizing the ostia of the coronary arteries in the late 1980's (1, 2), tremendous progress has been made in coronary MRA. However, to consistently acquire high-resolution, artifact-free coronary artery images in routine clinical studies is still challenging task. Coronary MRA is challenging because of the small vessel diameter (around 2 – 4 mm), complex geometry of the arterial tree, and continuous cardiac and respiratory motion of coronary arteries. Various strategies have been proposed to overcome these obstacles. For example, 3D imaging is currently used to cover the whole course of coronary arteries; parallel imaging techniques are employed to improve the resolution and/or reduce the imaging time; various cardiac and respiratory gating techniques are developed to minimize motion related artifacts. Various clinical studies have shown the coronary MRA has a relatively high sensitivity and negative predictive value, although specificity and positive predictive value need further improvement.

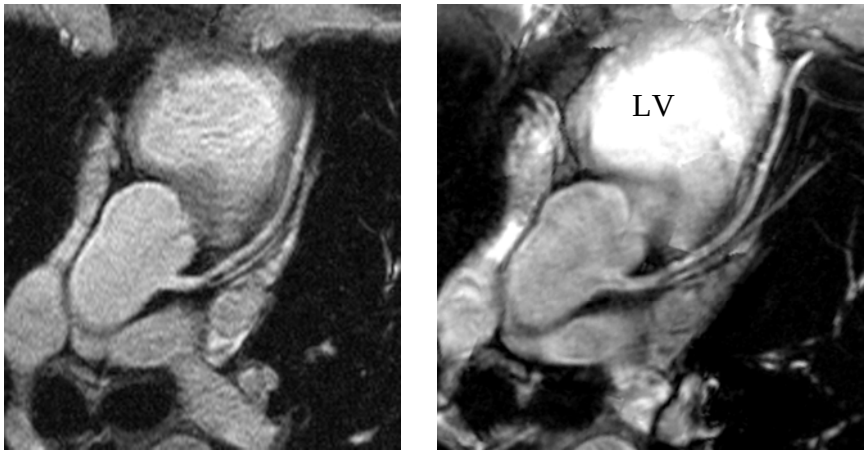
Despite all these progress, the spatial resolution, signal-to-noise ratio (SNR), and imaging time have always been competing factors in setting up of imaging protocols. Certain compromises need to be taken to reach the optimal tradeoff among these factors. 3.0T imaging has the potential to increases SNR that in turn allows increased spatial resolution and/or shortened imaging time, which is crucial for coronary MRA. High field imaging has achieved great success in functional MRI study of the brain based on the blood oxygenation level-dependent effect in the early 1990's (3). It has not been extensively used for in vivo imaging of the human heart until recently with improvements in gradient systems and receiving coils and increased availabilities for whole-body imaging (4-6).

Promises

SNR and CNR Improvements at 3.0T

The primary motivation of performing coronary MRA at 3.0T is increased SNR and CNR. The improvement in SNR can be used to increase the spatial resolution and/or reducing imaging time. In vivo human coronary MRA at 3.0T was first reported by Stuber et. al. in 2002 (7). Good quality coronary artery images were consistently acquired from nine consecutive volunteer studies with a navigator-guided free breathing T2-prepared gradient-echo sequence. The feasibility of performing coronary MRA at 3.0T using breath-hold, steady-state free precession (SSFP) sequence was demonstrated by our group (8). Comparison between 1.5T and 3.0T from the same volunteers showed 53% and 92% increases of SNR and CNR, respectively. A

comparison is shown in Fig. 1. The image quality at 3.0T was observed to be more variable than 1.5T using the SSFP sequence, with increased susceptibility artifacts and local brightening as the result of increased B_0 and B_1 inhomogeneities. A comparative study by Sommer et al using a navigator-guided free breathing, conventional gradient echo sequence also showed significant increases of SNR and CNR from 1.5T to 3.0T (9), although the theoretically predicted twofold gain in SNR at 3.0T was not achieved. Part of the reason was that a smaller flip angle was used at 3.0T because of specific absorption rate restriction.

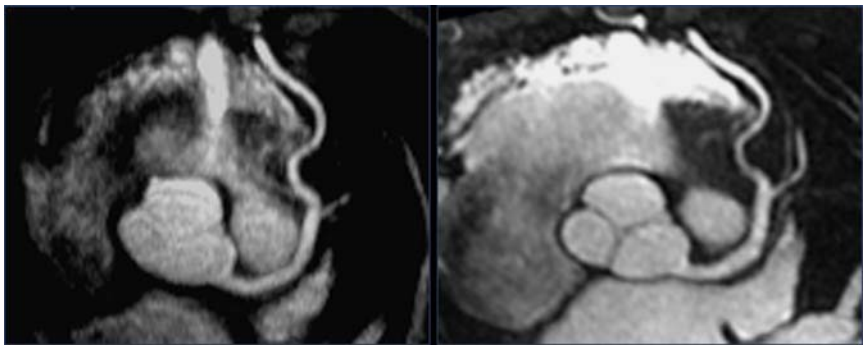


1.5T **3.0T**

Figure 1. Example of LAD images from one healthy volunteer at 1.5T and 3.0T. Note that the signal intensity and vessel delineation are substantially improved at 3.0T compared to that at 1.5T. Also note the increased signal heterogeneity at 3.0T as indicated by brightening in the left ventricle (LV).

Gadolinium based T1-shortening contrast agents have been shown to improve the depiction of coronary arteries at 3.0T (10) (Fig. 2). Increased T1 value of myocardium at 3.0T facilitates the suppression of background signals because longer inversion recovery time (TI) can be used after the inversion pulse. The increased TI allows more recovery of the desirable blood magnetization, yielding higher blood signal intensity. Because of the need for first-pass imaging, the images were acquired within a single breath-hold, which limited the spatial resolution of the images.

A newly developed Gadolinium based T1-shortening contrast agent, MultiHance (Bracco Imaging) has recently been shown to have higher T1 relaxivity and longer blood pool circulation. We have demonstrated that MultiHance allows slow infusion and longer acquisition time for free breathing coronary MRA.



1.5T **3.0T**

Figure 2. Maximum intensity projection images of the LAD after contrast agent administration at 1.5 and 3.0 T from the same volunteer. Measured SNR and CNR from 3.0-T image are 34.6% and 50.6% higher than those from 1.5-T image using same imaging sequence and spatial resolution. (Reprinted from reference 10)

Cardiac motion-resolved 3D coronary MRA were also successfully implemented at 3.0T with administration of clinically approved extravascular contrast agent (11). Continuous acquisition of coronary data in all cardiac phases eliminated the need of predetermining the trigger delay time and data acquisition window, which varied among subjects. Background signals (myocardium, epicardial fat) were suppressed by continuously applying RF pulses with relatively large flip angles.

Clinical studies were compared between 1.5T and 3.0T in 18 suspected coronary artery patients (9). It was found that visualized coronary artery lengths and image quality were the same at both field strengths. There were no statistically significant differences in the detection of coronary artery stenoses between coronary MR angiography at 3.0 T and coronary MR angiography at 1.5 T with respect to sensitivity ($P > .99$) and specificity ($P > .99$), as summarized in Table 1. An example of coronary artery disease detection is shown in Fig. 3. The spatial resolution was $0.9\times0.9\times3.0$ mm^3 (interpolated to $0.7\times0.7\times1.5$ mm^3). The imaging time was ~ 10 min with an average navigator efficiency of 38%. The segmented gradient-echo sequence was used for data acquisition during free breathing.

Table 1. Diagnostic Accuracy with Coronary MR Angiography at 3.0 and 1.5 T in Detection of Coronary Artery Stenoses

Variable	3.0 T	1.5 T
No. of true-positive results	14	14
No. of false-positive results	10	11
No. of true-negative results	80	80
No. of false-negative results	3	3
Sensitivity (%)*	82 [14/17] (60, 93)	82 [14/17] (58, 94)
Specificity (%)*	89 [80/90] (78, 94)	88 [80/91] (76, 94)
Accuracy (%)*	88 [94/107] (79, 93)	87 [94/108] (77, 93)

* Based on segment-by-segment analysis of proximal and middle segments of the coronary arteries. Data in square brackets are those used to calculate the percentages, and numbers in parentheses are 95% confidence intervals given as percentages. (Reprinted from reference 9)

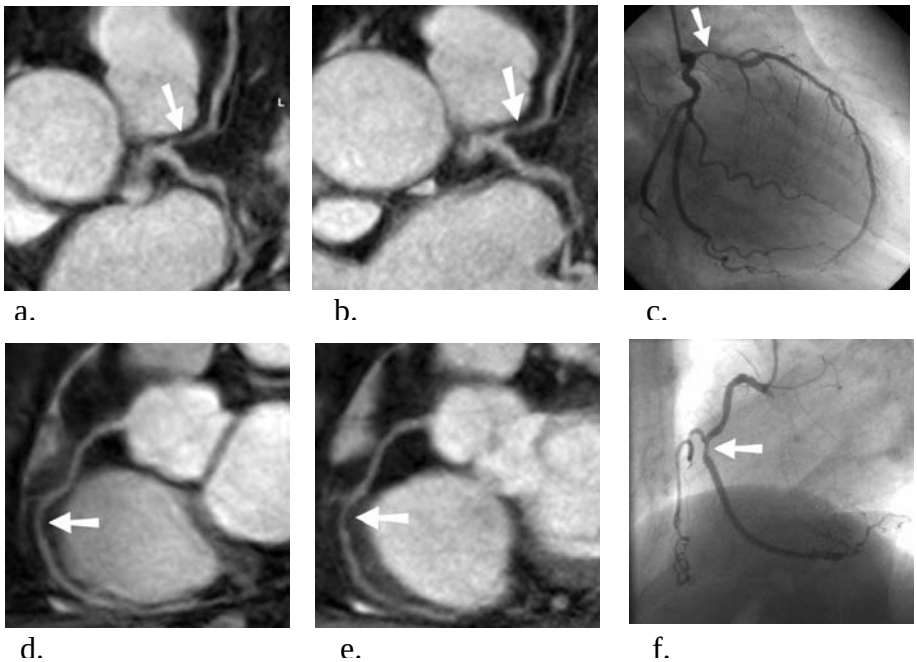


Figure 3. Comparison of muliplanar reformatted MR angiograms obtained at **(a, d)** 3.0 T and **(b, e)** 1.5 T in a 59-year-old male patient with severe disease in the LCA **(a-c)** and moderate disease in the RCA **(d-f)**, including stenoses in the LAD artery (arrow in **a** and **b**) and the RCA (arrow in **d** and **e**). **(c, f)** Conventional angiograms. At quantitative analysis, the LAD artery and RCA stenoses (arrow) were calculated to be 83% and 52%, respectively. At both field strengths, there is good correlation between the MR angiograms and the corresponding conventional angiograms. (Reprinted from reference 9)

Parallel imaging has been used to speed up data acquisition of coronary MRA at 3.0T. A previous study had shown coronary MRA at 3.0T using parallel sensitivity encoding (SENSE) (12) with a reduction factor of two for data acquisition. Nearly preserved image quality of coronary arteries was reported (13,14) (Fig. 4). An FOV of 360×270 mm^2 was sampled with a 512×270 matrix, resulting in an in-plane spatial resolution of 0.7 ×1.0 mm^2. Ten slices of 3 mm thickness were acquired and interpolated to 20 slices using zero-filling. Again, a segmented gradient-echo sequence was used for data acquisition.

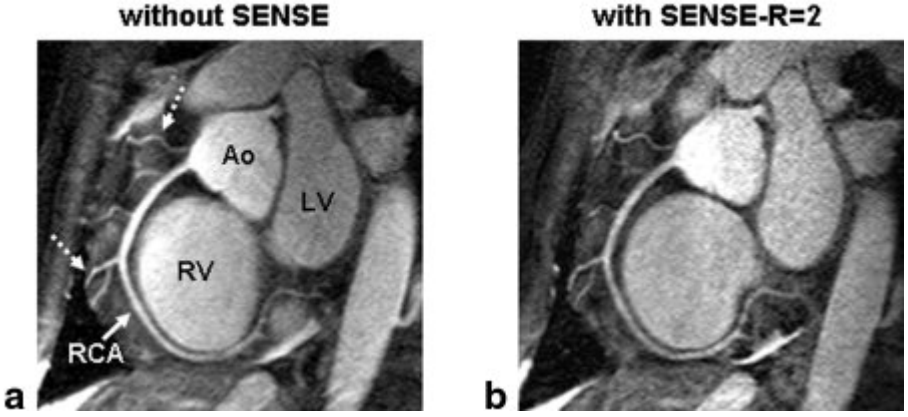


Figure 4. Example of a coronary MRA obtained without SENSE (**a**) and with SENSE-R = 2 (**b**). Besides the RCA, a number of smaller branching vessels are depicted (dotted arrows). RV = right ventricle, LV = left ventricle, Ao = aorta. (Reprinted from reference 13)

Major problems

1. Field inhomogeneity

A major problem associated with 3.0T coronary MRA is the increased imaging artifacts, especially for SSFP imaging and fat suppression. These artifacts can arise from increased B_0 inhomogeneity and frequency offset from tissue susceptibility variation at the heart-lung boundary. Such artifacts typically manifest as dark "banding" or ghosting of flow in the image. Typical strategies of suppressing such artifacts include summing frequency-modulated acquisitions (15), adjusting synthesizer frequency (16), applying localized linear or second order shimming corrections (5), maximizing the spectral width of the pass band by minimizing the repetition time (TR) of SSFP sequences, or improving the magnetization preparation of SSFP sequence (17).

Because of the problems with SSFP imaging due to field inhomogeneities, most coronary MRA studies at 3.0T used conventional (incoherent) gradient-echo sequence (FLASH: fast low angle shot) because it is much less sensitive to field inhomogeneities. However, the SNR of FLASH is substantially less than that of SSFP, which compromises the benefit of 3.0T imaging. We have shown that FLASH coronary MRA at 3.0T has similar SNR as SSFP at 1.5T. However, FLASH imaging generally provides more robust and consistent image quality and allows longer TR's to increase SNR and/or resolution. Nevertheless, research is ongoing to continue to explore ways to improve SSFP imaging at 3.0T.

2. Energy deposition

The FDA guidelines of the specific-absorption-rate (SAR) thresholds are 2 W/kg in the normal mode and 4 W/kg in the first level controlled mode. In the range of clinically used field strengths, SAR roughly increases quadratically with field strength. Thus, for a certain RF pulse with fixed bandwidth and flip angle, the SAR at 3.0T is about 4 times higher when compared with that of 1.5T. This can become a limiting factor in coronary MRA at 3.0T especially when SSFP sequence and T2-preparation are used. Compromises (for example, decreasing the flip angle or increasing the RF pulse duration) need to be made to comply with the safety regulations. Advanced RF pulse design can be helpful in maintaining short pulse duration as well as not inducing excessive power deposition (e.g., variable rate pulse).

3. Dielectric resonance and B_1 inhomogeneity

The wavelength of RF pulse decreases with frequency. At 3.0T, the effective wavelength of RF pulses becomes comparable to the size of human organs. Dielectric resonance occurs and induces local signal maxima. Dielectric effect is related to the shape of the object, size of the organs, and dielectric property of the subject. Dielectric resonance artifacts typically manifest as brightening near the center of the object. For coronary MRA, it may not directly impede the depiction of vessels. However, local signal and contrast behavior may be altered, which may impair the diagnosis of coronary disease. Signal intensity normalization is useful to provide uniform signals across the image.

Reduced penetration of RF pulses and increased dielectric resonance at high field lead to increased B_1 field inhomogeneity at 3.0T than 1.5T. In addition, increased eddy currents can counteract the applied gradients and compromise the performance of selective profile of RF pulses, or accumulate additional phase error in SSFP sequence. Utilization of B_1 insensitive RF

pulse (e.g., adiabatic pulse) (18) or application of buffer cushion filled with dielectric substance (19) might alleviate some of these B_1 inhomogeneity effects.

Summary

3.0T imaging of coronary arteries has gained increased interest in the past years. The SNR advantage at 3.0T warrants its further research. It has the potential to increase spatial resolution or reduce imaging time. With further development of fast imaging techniques and sequence design, 3.0T can potentially become a very promising platform of performing routine coronary MRA. However, preliminary patient studies have not translated the SNR benefit at 3.0T into more accurate disease diagnosis. Improved spatial resolution and speed with parallel imaging is a promising mechanism for taking advantage of the SNR gain at 3.0T. Conventional gradient-echo sequences (FLASH) are less sensitive to field inhomogeneities as compared to SSFP sequences (TrueFISP, b-TFE, FIESTA). With increased field inhomogeneities at 3.0T over 1.5T, conventional gradient-echo sequences are a robust technique for coronary MRA at 3.0T at the current stage. T1-shortening contrast agents can substantially increase the blood-myocardium contrast. Further development is still required to consistently acquiring good quality coronary artery images at 3.0T using SSFP. In conclusion, 3.0T imaging has great promise for coronary MRA but further technical developments are required for fully demonstrate the benefits of 3.0T due to its SNR gain.

References

1. Lieberman JM, Botti RE, Nelson AD. Magnetic resonance imaging of the heart. Radiol Clin North Am 1984; 22:847-858.
2. Paulin S, von Schulthess GK, Fossel E, Krayenbuehl HP. MR imaging of the aortic root and proximal coronary arteries. AJR Am J Roentgenol 1987; 148:665-670.
3. Turner R, Jezzard P, Wen H, et al. Functional mapping of the human visual cortex at 4 and 1.5 tesla using deoxygenation contrast EPI. Magn Reson Med 1993; 29:277-279.
4. Noeske R, Seifert F, Rhein KH, Rinneberg H. Human cardiac imaging at 3 T using phased array coils. Magn Reson Med 2000; 44:978-982.
5. Schar M, Kozerke S, Fischer SE, Boesiger P. Cardiac SSFP imaging at 3 Tesla. Magn Reson Med 2004; 51:799-806.
6. Hinton DP, Wald LL, Pitts J, Schmitt F. Comparison of cardiac MRI on 1.5 and 3.0 Tesla clinical whole body systems. Invest Radiol 2003; 38:436-442.
7. Stuber M, Botnar RM, Fischer SE, et al. Preliminary report on in vivo coronary MRA at 3 Tesla in humans. Magn Reson Med 2002; 48:425-429.
8. Bi X, Deshpande V, Simonetti O, Laub G, Li D. Three-dimensional breathhold SSFP coronary MRA: a comparison between 1.5T and 3.0T. J Magn Reson Imaging 2005; 22:206-212.
9. Sommer T, Hackenbroch M, Hofer U, et al. Coronary MR angiography at 3.0 T versus that at 1.5 T: initial results in patients suspected of having coronary artery disease. Radiology 2005; 234:718-725.
10. Bi X, Li D. Coronary arteries at 3.0 T: Contrast-enhanced magnetization-prepared three-dimensional breathhold MR angiography. J Magn Reson Imaging 2005; 21:133-139.

11. Bi X, Park J, Larson AC, Zhang Q, Simonetti O, Li D. Contrast-enhanced 4D radial coronary artery imaging at 3.0 T within a single breath-hold. Magn Reson Med 2005; 54:470-475.
12. Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: sensitivity encoding for fast MRI. Magn Reson Med 1999; 42:952-962.
13. Huber ME, Kozerke S, Pruessmann KP, Smink J, Boesiger P. Sensitivity-encoded coronary MRA at 3T. Magn Reson Med 2004; 52:221-227.
14. Huber ME, Kozerke S, Boesiger P. Improved artery delineation in dual-stack coronary magnetic resonance angiography using parallel imaging at 3 T. J Magn Reson Imaging 2005; 21:443-448.
15. Foxall DL. Frequency-modulated steady-state free precession imaging. Magn Reson Med 2002; 48:502-508.
16. Deshpande VS, Shea SM, Li D. Artifact reduction in true-FISP imaging of the coronary arteries by adjusting imaging frequency. Magn Reson Med 2003; 49:803-809.
17. Schar M, Boesiger P, Kozerke S. Considerations on startup sequences in interrupted balanced SSFP imaging at 3 Tesla. In: Proc. Intl. Soc. Mag. Reson. Med. 12. Miami Beach, FL, 2005; 249.
18. Nezafat R, Ouwerkerk R, Gharib A, Pettigrew R, McVeigh ER., Stuber M. B1 insensitive T2 preparation sequence for coronary imaging at 3T. In: Proc. Intl. Soc. Mag. Reson. Med. 12. Miami Beach, FL, 2005; 2794.
19. Schmitt M, Feiweier T, Horger W, et al. Improved uniformity of RF-distribution in clinical whole body-imaging at 3T by means of dielectric pads. In: Proc. Intl. Soc. Mag. Reson. Med. 11. Kyoto, Japan, 2004; 197.